**Coordination Studies with PNNL's Global Change Assessment Model:
Integrated Science Modeling and Applications to the Human
Dimensions**

Final Technical Report (October 1996-March 2000)

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Accomplishments (October 1996-March 2000)

This report outlines the progress on the development and application of Integrated Science Assessment Model (ISAM) supported by the DOE Program on Health and Environmental Research: Environmental Sciences Program under Grant No. DOE DFG02-96ER 62284. As part of this research proposal, we designed the model that better represent spatial variations and treat the process relevant towards evaluating the biogeochemical cycles important to determining atmospheric composition and resulting climatic effects at the regional scale. The process level understanding of regional impacts into the Integrated Assessment (IA) model will help to improve the understanding of climate change impacts and extend the range of issues, which can be addressed in an IA framework. On the application front, the newly developed model has been applied to a selected set of studies to address policy related questions on climate change, in particular, the role of forestry, and land-use for historical greenhouse gas emissions; projections of future methane emissions; a research study related to energy implications of future stabilization of atmospheric CO₂ content; and radiative forcing and estimation of a number of important greenhouse gases. In the following, the significant findings from the DOE supported study are outlined.

ISAM Carbon Cycle Modeling

Carbon Cycle Component of ISAM. The carbon cycle is the most complex and important cycle of the earth-atmosphere system. This cycle is complex because it involves the complicated and dynamic network flows of matter, in ever-changing form, between the many compartments of the global environment. The carbon cycle is also important due to man's interference with the natural global carbon cycle by burning fossil fuels and changing land use. Increasing amounts of carbon dioxide in the atmosphere may cause a detectable change of the global climate. As part of this research, a state-of-the-art model for the carbon cycle has been developed to predict the likely future changes in the atmospheric abundance of CO₂, as predicted by the use of fossil fuels, deforestation, and expansion of agriculture land. Indeed, the reliability of our model results, and the direct importance to policy makers, has made my carbon cycle model results one of the key contributions to the various international assessments (such as IPCC, WMO/UNEP). The carbon cycle component of ISAM was originally developed as a tool to predict future changes in atmospheric CO₂ levels, depending on fossil fuel use, deforestation and agricultural land expansion. This schematic model for the carbon cycle was constructed to be consistent with current understanding of the global carbon cycle. Testing the model's capability to represent this understanding has, in part, been based on the analysis of tracer records such as ¹³C and ¹⁴C (Jain et al., 1996). This model has also been inter-compared with 17 other carbon cycle models in a recent Intergovernmental Panel on Climate Change (IPCC) study, which showed the ISAM carbon cycle model to be a good representation of our current state of understanding of the global carbon cycle. Since 1995 IPCC assessment, our carbon cycle model has also been used to assess scenarios for future emissions.

Terrestrial Regional Carbon Cycle Model. As proposed, a terrestrial regional carbon cycle model has been developed to examine the regional pattern of carbon sources and sinks implied by land use changes and proposed mechanisms for the enhanced storage of biospheric carbon. The new model accounts for eleven land regions which each contain seventeen land-coverage classifications. Within each region and land-coverage classification, the carbon cycle is modeled. The carbon cycle includes the effects of biomass re-growth, CO₂ fertilization, and, potentially, climate change on productivity and carbon storage. We used a reconstruction of past land use change, nitrogen deposition, and CO₂ change to drive changes in this terrestrial carbon cycle model. We found a variety of regional, and consequently zonal, patterns of carbon sources and sinks the distribution of which depended on the assumed strengths of these effects. Our results compare well with those of more highly resolved models as well as with zonal estimates from atmospheric data. Application of this model to the reconstruction of past carbon cycles clarifies unresolved issues, and allows for inclusion of these issues in the integrated assessment of future climate and land-use change. The results of this study were presented at the Fifth International Carbon Dioxide Conference held in Australia (Kheshgi et al., 1997a).

Estimation of the Global Budget of Bomb-Produced Radiocarbon. Several recent studies of the global inventory of radiocarbon produced by aboveground nuclear weapons testing have brought into question our understanding of the global cycle of bomb-produced radiocarbon. This tracer provides a unique test for examining the performance of global carbon cycle models used in the analysis of global warming scenarios. In this study (Jain et al., 1997) we employed a model for the global cycles of carbon and its isotopes to examine the differences found in these studies. Our results indicated that several modeling approximations or assumptions could be responsible for the differences. In light of the considerable uncertainty in both model-based and data-based estimates of global inventories, I concluded that the global budget of bomb-produced radiocarbon cannot be shown to be out of balance. Our model-based analyses suggests that an improved analysis of the atmospheric tests and their production of bomb radiocarbon as well as addition measurements of ¹⁴C in the biosphere and ocean could significantly reduce uncertainties in model studies of the evolution of ¹⁴C in the carbon cycle system (Jain et al., 1997).

Estimation of the Uncertainty of Historical and Projected CO₂ using our Carbon Cycle Modeling System. We have used Bayesian analysis techniques to study the uncertainty of our current ISAM derived carbon budget based on the estimates of uncertainties in historical carbon dioxide and carbon isotopic records, as well as uncertainty in model parameters (Kheshgi et al., 1999a). In addition, we have also estimated the probability distribution of future atmospheric CO₂ concentrations for scenarios of CO₂ emissions. Bayesian parameter estimation makes use of prior estimates of model parameters along with data-based constraints to estimate the probability distribution of parameters of a global carbon-cycle/climate model. Data-based constraints used in this analysis include the trend in atmospheric $\delta^{13}\text{C}$, oceanic $\delta^{13}\text{C}$ in dissolved inorganic carbon, the pre-bomb decrease in ¹⁴C in the atmosphere and the mixed layer due to the *Suess Effect*, the bomb-¹⁴C in the mixed layer, the bomb-¹⁴C ocean inventory, the total bomb-¹⁴C inventory, and

the vertical distribution of total dissolved carbon and ^{14}C . We find that, for the model used and for the IPCC IS92a CO_2 emissions scenario, the estimate of pCO_2 in 2100 is 734 ± 98 ppmv (with a 90% confidence interval). This result is found to be sensitive to the choice of prior parameter information, model degrees of freedom, and model structure. For example, if the terrestrial biosphere's response to climate were known to follow modeled behavior, the projection of pCO_2 in 2100 becomes 740 ± 72 ppmv. Posterior estimates of model parameters are correlated, which causes the substantial uncertainties in oceanic and biospheric carbon sinks to cancel at the present, leading to small uncertainties in pCO_2 projections for the next decade which grow many fold by 2100. Factors not included in this study could significantly affect estimates. These include alternative model structures, additional climate drivers, such as aerosols, and other climate effects on carbon cycle, such as precipitation. A journal article is currently being written, which will be submitted to peer-reviewed journal for publication.

ISAM Atmospheric Composition Modeling

CH₄ Cycle Modeling. Methane (CH_4) is the second most important greenhouse gas emitted from sources related to human activities. CH_4 concentrations have risen rapidly since pre-industrial times, mainly due to increased human demand for food and energy from fossil fuels. Since the major portion of methane is emitted from sources directly under human control (including cattle raising, rice cultivation, waste disposal, and the use of natural gas), increasing attention is being focused on resolving the magnitude of the different methane sources and sinks, and their variations. The major goal of our methane-related research is to identify and quantify these sources, then predict CH_4 concentrations resulting from changes in these sources. We use our modeling capabilities and our background in modeling the methane cycle in the global atmosphere to address this issue. As we proposed, we also refined our current atmospheric composition module to enhance its capability for calculating CH_4 effects (Kheshgi et al, 199b). We used our 2-D zonally averaged model of the troposphere and stratosphere as a basis for evaluating the treatment of interactions between CH_4 , CO, NO_x , NMHCs, and OH and effect of methane. In most of the integrated assessment modeling studies for scenario analysis such interactions has been ignored. As we have shown in our recent study that neglecting the effects of CO, NO_x , and OH, estimated CH_4 concentrations could be as much as 20 % in error (Figure1, Kheshgi et al., 1999b). Results of this study clearly show that there is reason to consider emissions of NMHCs, NO_x , and CO in future strategies to control CH_4 concentrations.

Atmospheric Lifetime and Regional and Seasonal Distribution of Atmospheric Trace Gases. Many assessments have reported the atmospheric lifetimes for several CFC-replacement compounds, however they lack uniformity in terms of model used and various other conditions applied. We recognized the need for consistent analyses of lifetimes, wherein every detail is taken into account to perform a comprehensive study. In one of the recent studies, we evaluated the atmospheric lifetimes of 28 CFC-replacement compounds (HCFCs and HFCs) (Naik et al., 2000) using latest version of our two dimensional chemical transport model. This study concluded that consideration of

stratospheric losses was important in determining the lifetimes of most of the replacement compounds, which were omitted by the several of the previous studies.

In order to examine the sensitivity of the radiative forcing to the vertical, and regional and seasonal greenhouse gas distribution, we estimated regional and seasonal changes in the vertical distribution of greenhouse gas concentrations using our two dimensional chemical transport model (CTM) (Jain et al., 2000). *Figures 2,3 and 4* show the comparison of CTM estimated regional changes in vertical distributions of CH_4 , N_2O , and CFC-12 for the September-October current atmosphere. Figures 2 and 3 also show the CTM estimated distributions for CH_4 and N_2O for the pre-industrial atmosphere. These concentrations were used as an input to calculate the regional and seasonal radiative forcing, which are discussed below.

ISAM Radiative Transfer Modeling

Estimation of Radiative Forcing for Important Greenhouse Gases. We evaluated, in a consistent manner, the radiative forcing due to changes in the concentrations of various important greenhouse gases (Naik et al., 1999, Jain et al., 2000; Li et al., 2000). In general, IAM use a simple relationship to calculate the radiative forcing of greenhouse gases. These relationships come from diverse sources and are generally based on a single global and annual mean background atmosphere in combination with broad band radiative transfer model. Even the international assessments (such as IPCC and WMO) used these diverse results for their assessment of greenhouse warming impact. The unique aspect of our study is its attempt to resolve inconsistencies in previous evaluations of radiative forcings by adopting a uniform approach and investigate the role of spatial and temporal resolution in estimating radiative forcing due to thirty-nine important greenhouse gases using distributions of major greenhouse gases based on chemical transport model results and measurements, in combination with a more accurate modeling approach - a narrow-band radiative transfer model of the global atmosphere (Jain et al., 2000). *Figure 5* shows the estimated monthly mean radiative forcing changes as a function of latitude for the period 1765-1992 for major greenhouse gases. As a result of this study, we concluded that significant seasonal and latitudinal variations in the radiative forcing of major greenhouse gases exist because of their dependence on assumed temperature, water vapor, ozone and cloudiness, all of which vary with latitude and season. In addition, the use of height-independent vertical distributions for many of the greenhouse gases, as used in numerous previous studies, was shown to produce errors of several percent in estimated radiative forcings.

The regional and the seasonal radiative forcing of greenhouse gases were needed as input for our newly developed regional climate model, which is discussed below.

ISAM Climate Modeling

Coupled Atmosphere, Land and Ocean Climate Model. One of the main components of this proposal is the development and implementation of a 2-D (latitude and height) coupled atmosphere, land and ocean climate modeling system to assess regional climatic

effects. As a first step towards our goal, we successfully implemented a hemispherically-averaged, seasonal, coupled atmosphere, land and ocean climate model. This model has already been used to study the sensitivity of the seasonal response of temperature to different aerosols and greenhouse gas forcings, including their climatic feedbacks. These results were presented at the fall meeting of AGU (Hardiker et al., 1997). Now this version has been extended, as proposed, to include a zonally-averaged ocean model, which consists of mass balance and temperature equations for each ocean basin. The climate model takes into account land/ocean heat exchange, meridional heat flux, vertical advection and diffusion heat flux, and radiative heat flux. Seasonal, latitudinal and vertical distribution of atmospheric temperature are also simulated by the model. Model performance has also been evaluated relative to the historical and current atmosphere (Figure 6). A journal article will be written describing the model's framework; initial testing of the model relative to the historical and current atmosphere, and initial applications of the model, for comparison with published climate studies.

Application of ISAM for Policy Analysis

Analysis of the Substitution of Natural Gas in the Utility Sector

We have been studying the contribution of methane to the climatic impact of switching from coal to gas use in the utility sector. In a paper presented at the 8th Global Warming conference and recently published by the World Resources Review, we addressed the question of changes in methane emissions, in comparison to those of carbon dioxide and sulfate aerosols (Hayhoe et al., 1998a). In continuation of that study, we have produced a paper that has been submitted to Energy Policy (Hayhoe et al., 1998b). It evaluates the impact of natural gas loss and methane emissions from coal mines on the mitigating potential of coal-to-gas switching. The analysis also addresses the contribution of sulfur emissions and uncertainties in the radiative forcing of aerosols. The effect of a range of natural gas loss rates from 0.5% to 5% was found to be much greater than the current range of uncertainty of global coal mining emissions, which in part justifies the emphasis that has been placed by the literature on examining the uncertainty of natural gas loss rates while assuming fixed emissions of methane from coal. However, we concluded that the variables with the largest impact on the end result of fuel switching were SO₂ emissions and the radiative forcing associated with them.

Analysis of the Future Atmospheric Methane Concentrations in the Context of the Stabilization of Greenhouse Gas Concentrations.

One of the several issues we are studying relating to chemistry-climate interactions involves the relationships between changes in emissions and concentrations of methane relative to other climate and atmospheric chemistry factors. In one of the recent studies we used our Integrated Science Assessment Model in combination with our 2-D chemistry-transport model to study the impact of interactions between emissions of CH₄, CO, NO_x, and hydrocarbons on tropospheric OH and O₃. This study also addressed the climatic effects of these interactions on derived CH₄ concentrations and radiative forcing (Kheshgi et al., 1999b). Results of this study show that there is reason to consider emissions of NMHCs, NO_x, and CO in future strategies to control radiative forcing from greenhouse gases. Our model results show that the CH₄ concentrations are expected to decrease to below pre-anthropogenic levels if current CO and OH production/emission rates are maintained and

if CH₄ emissions are reduced to pre-anthropogenic rates. Radiative forcing of climate would be reduced, relative to BAU scenario IS92A, if anthropogenic CO, NO_x, CH₄ and CO₂ emission/production rates were reduced over the next century by the same relative extent. This would include stabilization of CO₂ at levels from 450 to 750 ppmv along specified time-pathways. In the scenarios studied, the reduction of radiative forcing due to changes in CH₄ concentrations would be more than 24% of that due to changes in CO₂ concentrations. If NO_x emissions were reduced less, this percentage would increase, but if additional reductions in CO sources beyond those projected in these scenarios were occur, the percentage contribution of methane relative to CO₂ would decrease.

Energy Implications of CO₂ Stabilization. The United Nations Framework Convention on Climate Change (FCCC) calls for stabilization of greenhouse gas concentrations. Any serious attempt to control greenhouse emissions must address the issue of energy supply. For continued economic growth with CO₂ stabilization, new, cost-effective, carbon-free technologies that can provide primary power on the order of 10 terawatts will be needed in the coming decades, in addition to improved economic productivity of primary energy. In *this study* we show, also for the first time to our knowledge, that implementing the UNFCCC mandate to stabilize atmospheric CO₂ in the 350–750 ppmv range can become increasingly difficult as the stabilization target decreases because of the lack of adequate carbon-free power (Hoffert et al., 1998). Even the central IPCC scenario will require carbon-free primary power by 2050 equal to our present global fossil-fuel-based primary power consumption.

The Impact of Atmospheric Chemistry on Weighting Indices. Weighting indices can be used to express emissions of different greenhouse gases (GHGs) in CO₂-equivalent terms. The choice of a specific weighting index is often thought to determine the emphasis on non-CO₂ GHGs in a multi-gas target. Although the choice of a 100-year Global Warming Potential (GWP) for the Kyoto Protocol does narrow the range of possible values, in a recent study we use the example of CH₄ to show that this choice does not constrain the GWP to a single number (Hayhoe et al., 1999). Projected changes in atmospheric CH₄ concentrations due to interactions with CO, NO_x, and OH produce direct GWPs ranging from 12.5 to 15.5. When the indirect effects due to tropospheric ozone (O₃) and stratospheric water vapor are included, GWPs range from 14 to 24. We also examine the impact of the calculated range in GWPs on the optimal contribution of CH₄ to emission reductions up to 1.0 GtC_{eq}. Our results show that for a 100-year GWP there is still significant variation in the effective use of CH₄ reductions in a multi-gas target. This has implications for the overall contribution of CH₄ and other non-CO₂ GHGs to both short-term and long-term strategies focussed on the mitigation of climate change impacts.

Scenario Analysis. We have also applied our ISAM to study number of policy related issues on climate change. The ISAM has been used to estimate the climatic effects of emissions from coal, oil, and gas use in electric power generation which are expected to result from fuel switching (Hayhoe et al., 1998). We have also applied our ISAM to calculate the climatic effects of different proposed Annex I CO₂ emissions limitations for global CO₂ emissions (Kheshgi et al. 1997b). ISAM carbon cycle model is becoming a

standard for United Nations assessments of CO₂ emission scenarios. The carbon cycle component of our ISAM has been used to assess IPCC scenarios for future emissions and concentrations (Wigley et al., 1997, Schimel et al., 1997). We have recently contributed ISAM carbon cycle model results to the upcoming IPCC Working Group I Third Assessment Report. Our carbon cycle and climate modeling results were also used by the IPCC WG I and III special report entitled "Aviation and the Global Atmosphere," to which D. Wuebbles and A. Jain also served as a contributing author (Prather and Sausen, 1999).

Review Study on the State of the Science of Global Climate Change. We have also written a review paper on the state of the state of the scientific understanding of the global change issues, such as the depletion of stratospheric ozone and the enhanced greenhouse warming, their potential impacts, and the relationships of scientific understanding to policy considerations (Wuebbles et al., 1999).

Figure Captions:

Note: The following 6 Figures can be found at ISAM web-site
<http://frodo.atmos.uiuc.edu/isam/doeproject>

Figure 1: Comparison of ISAM estimated methane concentrations for IPCC IS92a scenario with 2-D chemical transport model

Figure 2: Comparison of Chemical Transport Model-Based Distribution of CH₄ with Observation for September-October Preindustrial and Present Day (1992) Time Periods.

Figure 3: Comparison of Chemical Transport Model-Based Distribution of N₂O with Observation for September-October Preindustrial and Present Day (1992) Time Periods.

Figure 4: UARS and Chemical Transport Model-Based Distribution of CFC-12 for September-October Contemporary Time Period.

Figure 5: Estimated Seasonal and Latitudinal Dependent Changes in Radiative Forcing (Wm⁻²) for the Period 1750-1992 for CO₂, CH₄, N₂O, and Halocarbons.

Figure 6: ISAM Estimated Temperature Change (K) 1765-1990.

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